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Forest Fire, Drought, Restoration Treatments, and Carbon Dynamics: A Way Forward

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Abstract

In this paper we explore the current status of dry, frequent fire adapted forests in California relative to modern pressures on forest health and long-term carbon dynamics. We find that current forest structure and disturbance regime dynamics promotes large-loss disturbance events killing much the of green biomass in the forest, including large trees that are best suited for sequestering carbon in stable, long-lived structures. Highlighted recent events include numerous very large, high severity fires and the extensive drought/beetle mortality event impacting large sections of the Sierra Nevada forest. We then evaluate treatment opportunities designed to improve forest resilience to both fire and insects/pathogens through a combination of stand thinning and surface fuel treatments. We also highlight the opportunity for increased carbon uptake through modified stand structures designed to promote fewer, but larger tree distributions. Finally, specific policy recommendations are made in the context of long-term forest management that use carbon stability as a guiding principle for restoring compositions and structures that promote forest health and resilience to stress and disturbance, while providing for multiple other co-benefits.

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Introduction

The purpose of this paper is twofold. The first is to describe current forest health problems and demonstrate the increasing risk of carbon (biomass) loss to wildfire and other disturbance agents in California's interior forests where fire and drought stress appear far more prevalent than in the coastal forests of California, Oregon, and Washington. The second is to clarify the impact of forest fuel treatments on carbon stocks over time, and the implications of integrating them into the long-term forest management strategies of different forest owners in California. We believe these considerations will help policymakers and land managers better evaluate what efforts would be needed to increase long-term carbon-related benefits via investments in additional fuels treatments. It is important to recognize that while that the treatments we are considering here primarily seek to reduce live and dead fuels, they are more appropriately considered *forest health* treatments. These treatments are in alignment with large scale forest health and restoration objectives, where stands are deemed to be more stable in regard to persistent forest structure and resilient to large, severe disturbances that significantly alter forest cover. Thus, in addition to modifying potential fire behavior, the treatments are designed to ameliorate adverse impacts of fire, drought, bark beetle attacks, and other disturbances. Fuels treatments here refer to the combination of stand composition and structure manipulation to promote stands that are more resilient to fire, to promote reduced fire behavior when burned naturally, to shift carbon storage in forests from many small and vulnerable trees to fewer large and resilient trees, and to prevent conversion of forested area to grasslands, shrublands, and hardwood forests that all typically support lower carbon stocks.

Treated forests will continue to be impacted by fire and other agents. Managed forests that have modest surface fuel profiles and are composed of fewer large trees, however, are likely to be less water-stressed under both drought and higher evaporative demand that is predicted under rising temperatures associated with climate change. Both of these features should act to mitigate large losses of standing green biomass in live trees and thus preserve the functional persistent role of forests to continue to store carbon. At the heart of this discussion is the belief that treatments enhance long-term forest carbon stocks by reducing stem competition for resources and creating more resilient forest structure to drought, insects and disease, and wildfire, thereby enhancing the suite of ecosystem services that dry conifer forests provide.

Setting the Stage – Modern-Era Structure and Conditions in Dry, Fire-Adapted Conifer Forests

It is widely recognized that fire has a major ecological influence on structure and function of western dry forests (Agee 1993, Sugihara et al. 2006), and that current forests that have been subject to modern era pressures (largely fire exclusion) have resulted in increased stand densities, smaller mean tree size, and increased accumulations of fuel in both surface and ladder strata (Lyderson et al. 2013). While the modern burn probability is hard to predict for any single project or site, both modeling and empirical analysis reveal that after many decades of successfully limiting fire to a fraction of pre-European settlement rates, burn rates are increasing in conifer forests throughout the west, and are likely to increase further due to climate change (Westerling et al. 2006, Westerling et al. 2011, Dennison et al. 2014). In addition, the increasing size of individual wildfires is resulting in larger patches of complete overstory tree mortality (Miller et al. 2009, Miller & Safford, 2012) which can remove fine scale habitat elements (Smith 2000), and limit natural conifer regeneration due to lack of seed source (Carlson et al. 2012, Collins and Roller 2013). The visual appearance of modern land management on forest structure is widely apparent in photo-reconstructions, such as that provided by Gruell (2001). Additionally, recent drought-influenced conifer mortality provides evidence of the instability of modern dry forests in the face of disturbance.

This paper addresses a number of planning efforts related to forest and climate change, including the Forest Carbon Action Plan, The California Energy Commission's Biomass to Energy Program, and the AB 32 Scoping Plan[1]/SB 350 related to natural and working lands within the objectives of decreasing avoidable emissions from wildfires and increasing carbon stored in California's forested landscape. The paper also acts as a technical supporting document for CAL FIRE's Forest Health Initiative, which is trying to coordinate implementation of various forest management programs (conservation, reforestation, forest improvement, etc.) intended to increase forest cover, forest health, and carbon stored in forested landscapes.

The following suite of findings and observations provide a knowledge base from which to approach understanding current conditions as they relate to forest carbon:

- Many California forests currently have considerably higher live carbon stocks than they did historically (Collins et al. 2011), but much of that stock is in smaller trees and in the dead pool, which are more vulnerable to fire (Lydersen et al. 2013, Earles et al. 2014). The ingrowth of small trees under the main canopy increases the likelihood of fire reaching the overstory canopy, where it can result in higher overall severity and the death of large trees. Historically, the low- to mid-elevation dry mixed and coniferous forests in California were highly variable, but in general were largely comprised of fewer, very large trees (Collins et al. 2011, Stephens et al. 2015). These historical forest structures were considered to provide more stable carbon storage than contemporary forest given the overall resilience of historical forests to disturbance (Sugihara et al. 2006, Hurteau and North 2009, North and Hurteau, 2011, Stephenson et al. 2014). Plainly stated, the current stocks of aboveground carbon are not stable and are likely to show significant losses over a 50 to100 year horizon.

The following are important distinctions in the quantity and quality of forest carbon pools in current low- to mid-elevation dry mixed and coniferous forests where wildfire has been effectively excluded, compared to treated or historic forest conditions:

- Higher densities of small trees are present, rather than fewer, more openly-spaced large trees characteristic of historic forests (North 2012, Stephens et al. 2015).

[1] AB 32 is the California Global Warming Solutions Act of 2006.

- There is more competition and higher impact to individual trees from drought and other stressors, which can be further impacted by climate change, leading to stunted growth and sequestration rates (Stephenson et al. 2014, Bennett et al. 2015).
    - Growth of large trees is impacted by drought to a greater degree than that of small trees (Kerhoulas et al. 2013, Bennet et al. 2015).
    - Stressed trees can take up to four years after the stressor abates to recover, significantly impacting sequestration rates throughout that time (Anderegg et al. 2015).
    - Large trees surrounded by an overgrowth of smaller trees increases the risk of large tree mortality from bark beetle attacks (Smith 2005).
    - Overly dense stands result in increased stress and mortality due to competition, drought, and disease, shifting more carbon to dead rather than live carbon pools (Earles et al. 2014).
- Fire suppressed forests are seeing a change in forest structure, with fire adverse species outgrowing the fire resilient trees historically common in California forests. This significantly reduces the resilience of our forests to future disturbance.
- There are fewer large trees on the landscape overall, with faster sequestration of carbon relative to smaller trees, and greater resilience to disturbance, hence stabilizing carbon sink in forests over time (North et al. 2009, Stephenson et al. 2014).
- Forest structures that promote higher severity wildfire are now common (Stephens et al. 2015). While many forests continue to sequester carbon, it is in pools that are at greater risk to losses over time as more of the carbon transitions from live to dead pools due to wildfire, drought, and other mortality-inducing agents (North and Hurteau 2011, Earles et al. 2014, Wiechmann et al. 2015).
- Short-term forest carbon emissions over the months of active burning of a severe fire can exceed the annual emissions of a major city, and those emissions typically occur late in summer when air quality is at its worst. The dramatic plume of a wildfire can capture attention, but where fire burns at high intensity through forests, the plume emissions represent approximately 15% of the forest carbon, the remaining 85% of which will decay and emit its carbon over subsequent years (Matchett et al. 2014, Hicke et al. 2013, Campbell et al. 2009, Campbell et al. 2016, Ryan et al. 2010).
- Wildfires emits over 60 percent of the PM2.5 (particles less than 2.5 micrometers in diameter) that California emits in total (CARB 2016). Under climate change conditions and with no change in forest health, wildfires are estimated to emit significantly more PM2.5 by the year 2100 (Hurteau et al. 2014), perhaps undoing the significant progress California has made to reduce PM2.5 emissions across the state.

- Higher risk of loss to catastrophic wildfire will result in less ability afterwards to restore carbon storage due to decreased survivorship of trees in general, especially if large trees are lost (North and Hurteau 2011), and a diminished ability to regenerate which may lead to longer term conversions to vegetation types with lower carbon carrying capacities (Ryan et al. 2010, Carlson et al. 2012, Roccaforte et al. 2012, Dore et al. 2012).
    - A recent study commissioned by the California Air Resources Board (CARB) found that California forested areas that converts to shrubland for long time periods after fire will be able to store less than 10 percent of the amount of carbon it stored pre-fire. Worse, if grasslands replace forests after severe wildfire, the resulting grassland will store less than 2 percent of the carbon of the forests that were replaced (Gonzalez et al. 2015).
    - Forests that burn at high severity are susceptible to reburning at high severity in the near future, making subsequent carbon storage on those lands unstable (Coppoletta et al. 2016).
    - A single large old-growth pine tree stores approximately the same amount of carbon as over a thousand 30 year old fir trees (M. Hurteau, Univ. of New Mexico, Albuquerque, personal communication). The loss of old-growth trees represents a carbon loss that cannot be restored to the landscape in under a century.
    - Where drought and bark beetle attacks have produced significant mortality, subsequent low severity fires can result in no post-fire regeneration, as the seed-producing trees were dead pre-fire and the low-severity fire destroyed the existing seed stock and sapling growth (Harvey et al. 2013)
- Statewide estimates show losses of total aboveground live carbon between 2001 and 2010, a time period when the prevailing forest management strategy was no treatment (Gonzalez et al. 2015). At the site-specific scale, a separate study observed a similar trend in their plots in the Sierra Nevada (Wiechmann et al. 2015). Between 2002 and 2011, their control plots in mixed-conifer forest lost approximately 16 Mg of carbon per hectare of live tree carbon, while two of their treatment plots, prescribed burn and understory-thin, accumulated 19 and 47 Mg of carbon per hectare, respectively, during the same time period.
    - These studies took place during the first decade of the 21st century, when the Sierra Nevada received an average amount of snowpack (averaged across all 10 years) and an average of 110,000 acres burned on the west slope. In the three to four years since the studies terminated, the snowpack has averaged less than 35 percent of normal and the fire seasons have averaged 220,000 acres. This suggests the observed decline took place under relatively positive growing conditions, and that the decline in carbon stored has likely become worse since the studies ended due to water stress limiting productivity and tree mortality.

The Changing Norm – Trends in Wildfire, Forest Health and Climate

Wildfires in California's coniferous forests have become larger and more uniformly severe over the last two decades (Miller et al. 2009, Mallek et al. 2013, Miller and Safford 2012) and it is reasonable to predict that this trend will continue to increase unless the pace and scale of forest restoration dramatically increases. Factors related to wildfire trends include:

- Annual burn rates in conifer forests under the current land management regime of increasing expenditures for fire protection continue to rise statewide (Figure 1). In particular, conifer forests show marked increases in burn rates since 2000 (Figure 2.) Of particular concern are conifer forests in the Sierra Nevada, which are burning at roughly three times the rate since 2000 as compared to the previous 30 year average (CAL FIRE-FRAP, unpublished data). In this regional-fuel type, current annual burn probabilities have gone above one percent, and climate model predictions show further increases expected throughout the century (Hurteau et al. 2014).
- By the 2016 fire season, the 2010-2019 decade set the modern record for acres burned on the western slope of the Sierra Nevada, with three fire seasons remaining in the decade. This decade's fire seasons in this area have averaged 170,000 acres burned, up 50,000 acres from the second highest recent decade (Figure 3).
- More acres have burned in the each of the last two decades than any other decade in the modern record.
- High fire severity is increasing, from an average of about 20 percent high severity 30 years ago to nearly 30 percent now (Miller and Safford 2012). The 2013 Rim Fire was nearly 40 percent high severity by burned area, the 2014 King Fire was almost 50 percent high severity, and fires during 2015 were estimated to have killed 13.5 million conifer trees – excluding information from the Butte, Dodge, Jerusalem, Nickowitz, Rocky, Valley, and Wragg fires (not all of which were in dry conifer forests). A recent study indicates that current rates of high severity fire in targeted California Spotted Owl nesting habitat will result in severe fire burning an area equivalent to the total area of nesting habitat utilized in 75 years (Stephens et al. 2016).
- While some recent studies dispute the findings of increased rates of high severity fires in California's interior forests (e.g., Williams and Baker 2012, Odion et al. 2014, Hanson and Odion 2014), these findings have been widely challenged due to (1) methods and interpretations of historic records and their influence on defining land-types for assessing fire regimes, and (2) the misconception that stand age as recorded in Forest Inventory and Analysis (FIA) data can be used as a proxy for time since last disturbance (Fulé et al. 2014, Stevens et al. 2016). Fulé et al. (2014) concluded:

  > *"…the preponderance of scientific evidence indicates that conservation of dry forest ecosystems in the western United States and their ecological, social and economic value is not consistent with a present-day disturbance regime of large, high-severity fires, especially under changing climate."*

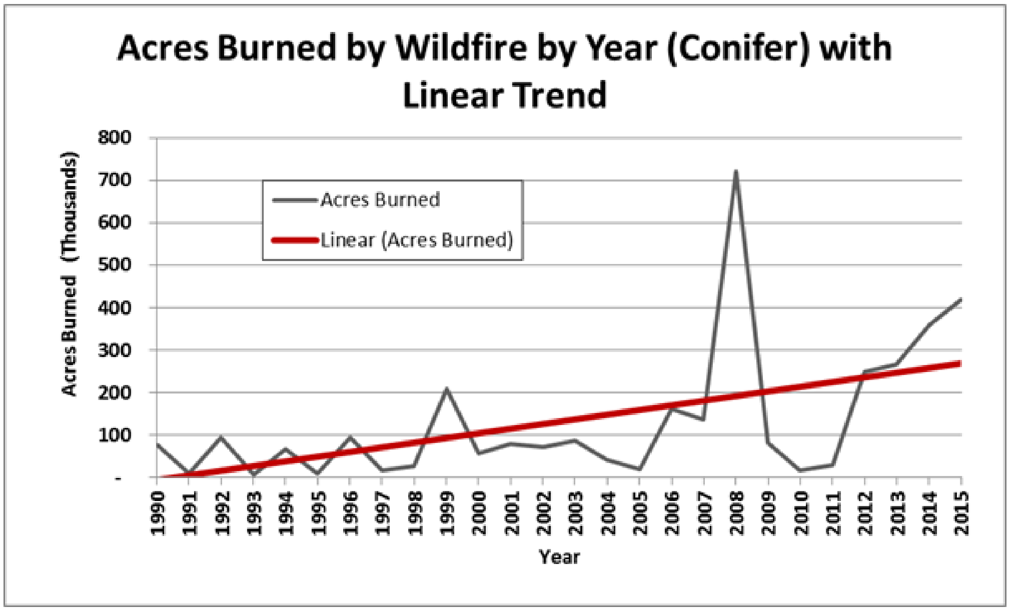

Figure 1. Annual acres burned in California from 1960-2014 and time-series linear model. (Source: CAL FIRE-FRAP unpublished data; FRAP Assessment, in progress).

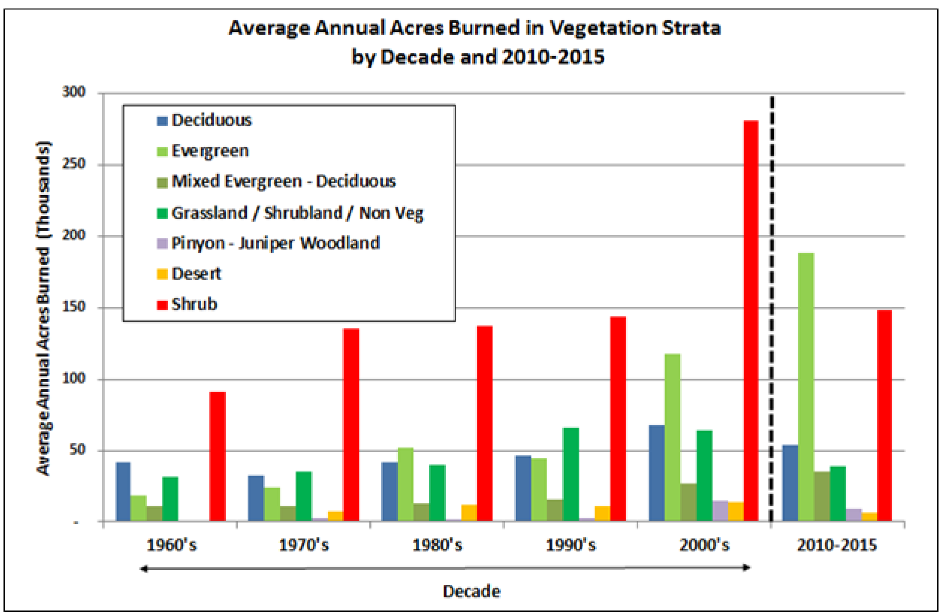

Figure 2. Decadal mean annual burn rate by vegetation type, 1960's- 2010's (abbreviated). (Source: CAL FIRE-FRAP unpublished data; FRAP Assessment, in progress).

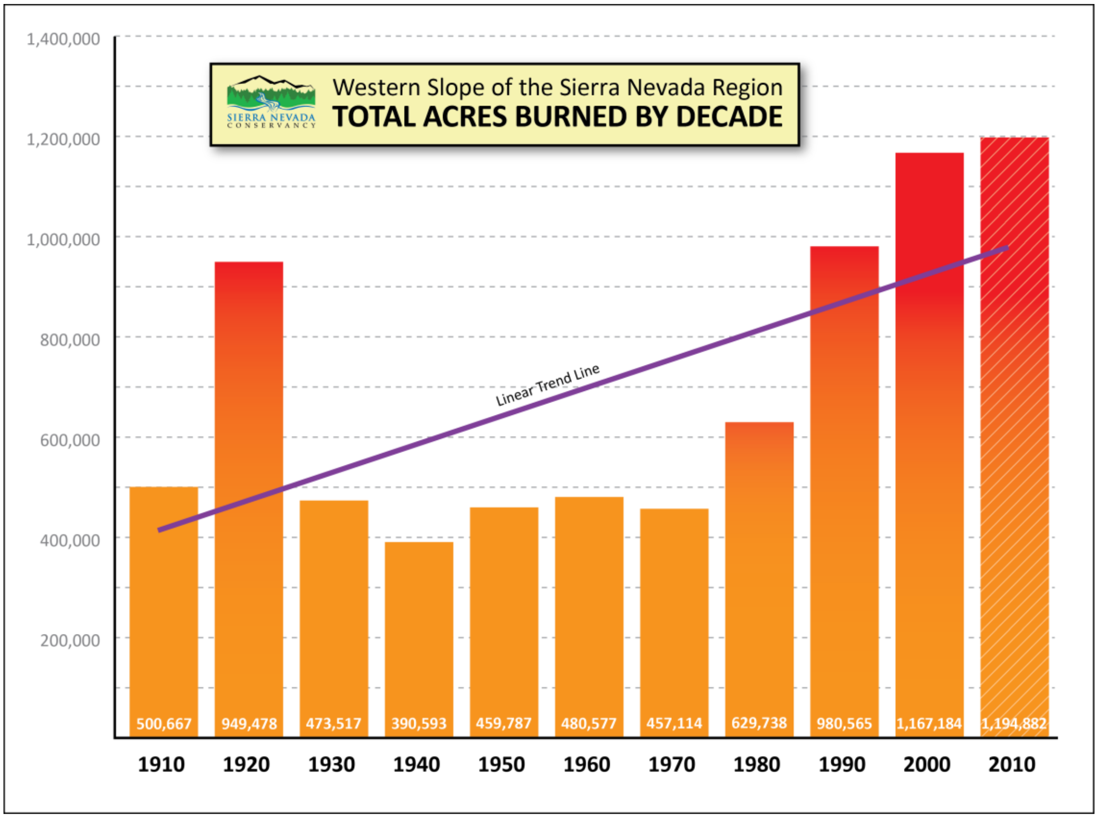

Figure 3. Decadal average annual burn area for west-slope Sierra Nevada Bioregion, 1910 – current. (Source: Sierra Nevada Conservancy). Note – At the time this graphic was produced, the 2010 decade had 3 fire seasons remaining and are not included.

Climate change can exacerbate existing stressors on the forest and affect carbon sequestration rates, and the quantity, quality, and stability of carbon stocks. Future climate change scenarios predict increases in temperature, increases in atmospheric CO2 concentrations, and changes in the amount and distribution of precipitation, all of which can act as stressors on forests.

- Extended drought and earlier snowmelt may become the new standard, as southern California is expected to see conditions up to 30 percent drier and 1-2 degrees (Fahrenheit) hotter than historical norms in the next 15 years (Krist et al. 2014).
- Severe wildfire can further intensify snowpack reduction issues, as the snowpack is exposed to direct sunlight and wind for 15 years or more until the canopy recovers.

Climatic influence on disturbance regimes (timing, frequency, and magnitude of wildfires; pest infestations) is already having an effect on California forests.

- Increasing temperatures and decreasing precipitation exacerbated by climate change contributes to dry and hot conditions favorable for wildfires, thereby increasing the risk for wildfire even more. Fire seasons in the west have already increased by 78 days since the mid-1980’s (Westerling et al. 2006).

- California conifer forests evolved over the centuries with frequent disturbance, making them resilient to climate change impacts when healthy. The resilience of these forests is now low, as they are far from their historic conditions. Additionally, mature healthy stands are generally resilient, but recent evidence suggests that once high severity fire removes the mature trees, conifer regeneration is uncertain (Collins and Roller 2013). Furthermore, high severity fire can promote vegetation and fuel conditions that allow for repeat high severity fire in short succession (Coppletta et al. 2016).
- Recent analysis projects increases in large wildfire occurrence, area burned, and emissions under a range of climate and human development scenarios in California (Westerling et al. 2015, Westerling et al. 2011, Hurteau et al. 2014).

In 2016, much of California is in the fifth year of a severe drought, making many forests less resilient to wildfire and more susceptible to bark beetles. In a cyclical fashion, increased beetle activity from climate change leaves behind greater tree mortality, which in turn can contribute to more severe wildfires over the next decade, as fine surface fuels and shrubs increase, and longer-term due to emissions from decomposition of dead tree materials (Hicke et al. 2012).

- Aerial detection surveys conducted by the USDA Forest Service for the period of 2010-2016 estimate a total of 66 million dead trees, largely concentrated in the southern Sierra Nevada region (Figures 4–7).
    - Approximately 29 million new dead trees were found in 2015.
    - By May of 2016, another 26 million trees are estimated to have died based on a limited survey only covering a small portion of the western slope of the Sierra Nevada.
- Even if California experiences several consecutive wet years in a row, it will take up to four years for the tree mortality rate to drop back down to average.

According to the USDA Forest Service risk assessment, California is at risk of losing at least 25 percent of its standing live forests due to insects and disease over 5.7 million acres, or 12 percent of the total forested area in the state (Krist et al. 2014; Table 1).

Table 1. Statewide summary of expected insect and disease risk areas by 2025 (Source: Krist et al. 2014).

State	**Risk area (acres)**	**Treed area (acres)**	**State area (acres)**	**% of state with trees**	**% of treed acres at risk**
California	5,697,000	47,237,000	101,218,000	47	12

- There are five National Forests in California facing significant losses from insects and disease on a large percentage of the forested land base, as summarized in Table 2.

Table 2. Five California National Forests with very high levels of expected tree loss from insects and disease (Source: Krist et al. 2014).

National Forest	Treed area (1000 acres)	% treed	Total BA loss (1000 sq. ft)	BA loss rate, %	BA loss rate (sq ft./acre)	Area at risk (1000 acres)	% of treed area at risk
Modoc	1,743	88	32,005	32	18	675	39
Lassen	1,333	97	44,180	28	33	651	49
Sierra	1,317	93	47,380	27	36	480	36
Tahoe	1,199	99	31,494	18	26	353	29
Plumas	1,379	99	34,569	18	25	320	23

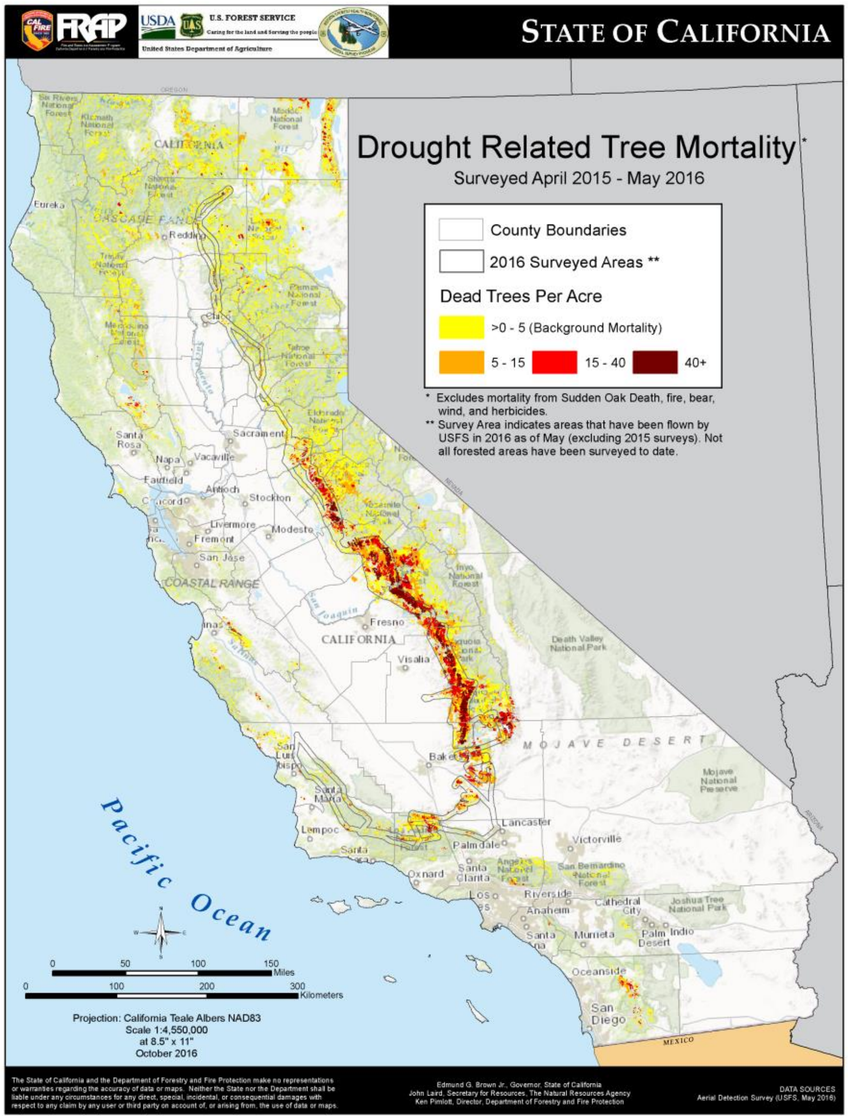

Figure 4. Annual Aerial Detection Survey of tree mortality, 2015 (Source: USFS Region 5 Forest Health and Monitoring, surveys April – September 2015)). Online data viewer available at: **http://egis.fire.ca.gov/TreeMortalityViewer/**

Figure 5. Broad overview of lowland pines along the southern Sierra Nevada Range, Sequoia National Forest. Photo credit: USFS Region 5 Forest Health Protection, State and Private Forestry, July 2015.

Figure 6. Intense pine mortality near Goodmill on the Hume Lake Ranger District of the Sequoia National Forest. Photo credit: USFS Region 5 Forest Health Protection, State and Private Forestry, April 2015.

Figure 7. East shore of Bass Lake, Bass Lake Ranger District, Sierra National Forest. Photo credit: Larry Swan, USFS Region 5 State and Private Forestry, November 2015.

- Some species are expected to lose significant amounts of their total basal area due to insects and disease, as summarized in Figure 8. It should be noted that this projected basal area loss is throughout the range of the species, so it could manifest as scattered pockets of mortality across a large area and not necessarily large swaths of mortality in a concentrated area.

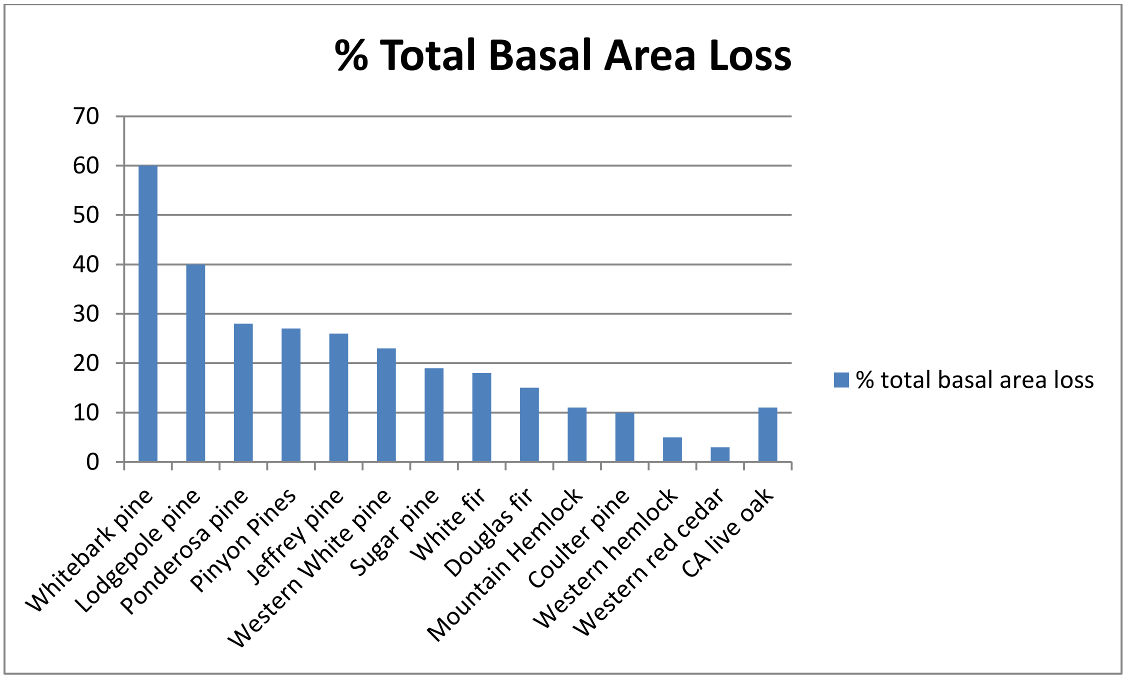

Figure 8. Estimated basal area losses by species from insects and diseases in California by 2027 (Source: Krist et al. 2014).

- Krist et al.'s (2014) estimates do not account for future changes in climate or current drought conditions, so the number of acres at risk is expected to be significantly higher.

As climate change continues to exacerbate the potential for drought, wildfire, insects, and disease, California's overstocked and unstable forests remain at severe risk of loss in the absence of management activities that reduce competition and introduce a mix of tree species that are adapted to the local environment. The goal is to create forests more resilient to disturbances and less susceptible to forest pests and high intensity wildfire.

Fuel Treatments and Carbon

Fuel treatments in their various forms (e.g., thinning small and intermediate trees to reduce ladder fuels, mechanical surface fuel treatments, broadcast prescribed fire) reduce stand densities and fuel loads, restore the structure and composition of fire-excluded forest ecosystems, and lower the potential for damaging, high-severity fire (Stephens et al. 2009, Campbell et al. 2009, Hurteau and North 2008, Hurteau and North 2009, North et al. 2009). Treatments have also been shown to improve resilience to drought (van Mantgem et al. 2016) and to increase the rate of carbon sequestration of the stand (Dore et al. 2012).

Although treatments may result in short-term forest carbon losses through biomass removal, carbon can quickly be recovered to pre-treatment levels if large, fire-tolerant overstory trees are not removed in large quantities (Stephens et al. 2009, Hurteau and North 2010, Wiechmann et al. 2015). This shifts the forest carbon stock from many small, vulnerable trees and the dead pool to large, resilient trees and the live carbon pool. These treatments can also lead to increased tree vigor (Collins et al. 2014), longer-term stability of the carbon sink, and increased quality in terms of:

- Decreased risk of loss to catastrophic wildfire.
- Increasing carbon sequestration rates over time.
- Increased carbon stored in live biomass compared to dead.
- Shifting carbon storage from small, vulnerable trees to large, resilient trees.

In the absence of fire, untreated forest stands may store more total carbon over long time periods (e.g., 100 years) than treated stands. However, the dense, overstocked condition of these forests place them at a higher liability for carbon loss from wildfire and insects/pathogens. Tree-based carbon stocks can be protected by treatments that produce low density stand structures dominated by large, fire resistant trees (Hurteau and North 2009, North et al. 2009, North and Hurteau, 2011).

While the exact impact that forest management activities have on carbon is very site-specific, some general trends from mechanical treatments on forest carbon stocks compared to a no-action scenario are summarized in Table 3 (extrapolated from Raymond et al. (2015) and Reinhardt and Holsinger (2010)).

Table 3. Summary of trends comparing treated and untreated dry-forests (interpreted from Reinhardt and Holsinger 2010 and Raymond et al. 2015).

	Untreated, no action scenario	**Treated, thinning scenario**
Total C, baseline	Higher	Lower
Total C, 50 years out	Higher	Lower
Amount of C in live pools	Lower	Higher
Carbon Sequestration rate	Decreasing	Increasing
Risk of loss to catastrophic wildfire	Higher	Lower

Wiechmann et al. (2015) offer evidence that a one-time treatment can yield positive carbon benefits. By ten years post-treatment, these researchers found that the immediate carbon reductions from both a prescribed burn treatment and an understory thin treatment had been re-sequestered within the remaining trees. Results from this study highlight the potential benefits to carbon storage of first entry treatments under current conditions.

Wood Products and Bio-Energy

Carbon may still remain stored for long-periods of time in harvested wood products. Shifting forest carbon into harvested wood products may increase the overall sequestration of the forest by freeing up more of the carbon carrying-capacity of new trees to take on additional carbon while allowing carbon to remain stored in off-site pools.

In the case of carbon emissions from using biomass for energy production, it can displace emissions from fossil fuel-based energy production and reduce emissions from open pile burning that is already occurring. Biochar, a byproduct of bioenergy production, is a soil amendment that can store forest carbon for a thousand years. Steady biomass supply will be necessary to increase biomass energy production infrastructure in the state.

A Way Forward: Recommendations and Policy Implications

We offer the following policy recommendations to support carbon stability in the face of wildfire and other carbon-limiting agents:

- Fund restoration treatments on forests that are overstocked and/or have high fuel loads with increased likelihood for catastrophic fire.
- Expand the use of prescribed and managed fire.
- Fund maintenance treatments to allow for the persistence of stability in the carbon sink.
- Fund bioenergy facility development and incorporate forest bioenergy targets into California's energy portfolio to reduce open pile burning.
- Recognize that forest conditions on some land ownerships may have more need for treatment than others.
- Allow for monitoring and adaptive management, using early projects as test beds to monitor both stand recovery and impacts on future wildfire.
- Allow for goals to minimize impacts from fire emissions.
- Develop carbon policy that focuses on the full carbon lifecycle.
- Recognize the current overgrown forest system as unnatural and unhealthy.
- Recognize that the current overgrown forests are a man-made situation and therefore out-of-control wildfire events should be recognized as a man-made event.

- Create incentives for landowners to restore their forests in cooperation with local and regional efforts, including collaborative, Integrated Regional Water Management Plans and use of the Sierra Nevada Conservancy's Watershed Improvement Program.
- Recognize that managed and prescribed fires are emulating natural processes in these forests and should be encouraged.
- Promote a landscape and systems approach to looking at forest management, where plans for projects include the influence of all treatments across all ownerships.

We believe that actively engaging in these policies will stem the tide of the dramatic pattern of declining forest health shown by recent wildfires and drought-induced tree mortality, and promote California's forests to store atmospheric carbon in long-term healthy and resilient forests.

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